

# CONTINENT-SCALE WRENCHING OF SOUTHWESTERN LAURUSSIA DURING THE OUACHITA-MARATHON OROGENY AND TECTONIC ESCAPE OF THE LLANO BLOCK

Thomas J. Algeo

H. N. Fisk Laboratory of Sedimentology  
Department of Geology  
University of Cincinnati  
Cincinnati, OH 45221-0013

## ABSTRACT

Existing paleotectonic models for the southwestern margin of Russia during the Ouachita-Marathon Orogeny call for continent-scale wrenching of either predominantly sinistral (mainly along the Amarillo-Wichita Uplift) or predominantly dextral (mainly along the Texas Lineament *sensu lato*) character. In addition, the conventional view has held that structural promontories such as the Llano Uplift came into contact with the Gondwanan lithospheric margin before adjacent structural embayments, a scenario requiring relative northwestward displacement of the Llano block, which is inconsistent with shear sense along both bounding lineaments. Available data are best reconciled by a model in which first eastern North America (the Alleghenian Orogen) and then the ancestral Mexican Peninsula collided with Gondwana, setting up transpressional wrench systems on both the northern and southwestern margins of the Llano block. Owing to differences in orientation of the Amarillo-Wichita Uplift (N70W-S70E) and the Texas Lineament (N55W-S55E) and to the convergent nature of wrenching, the maximum principle stress axis within the Llano block was oriented roughly NNE-SSW during middle-late Pennsylvanian time. This resulted in southeastward displacement of the Llano block relative to the adjacent North American craton and ancestral Mexican Peninsula until contact with the Gondwanan lithospheric margin inhibited further "tectonic escape."

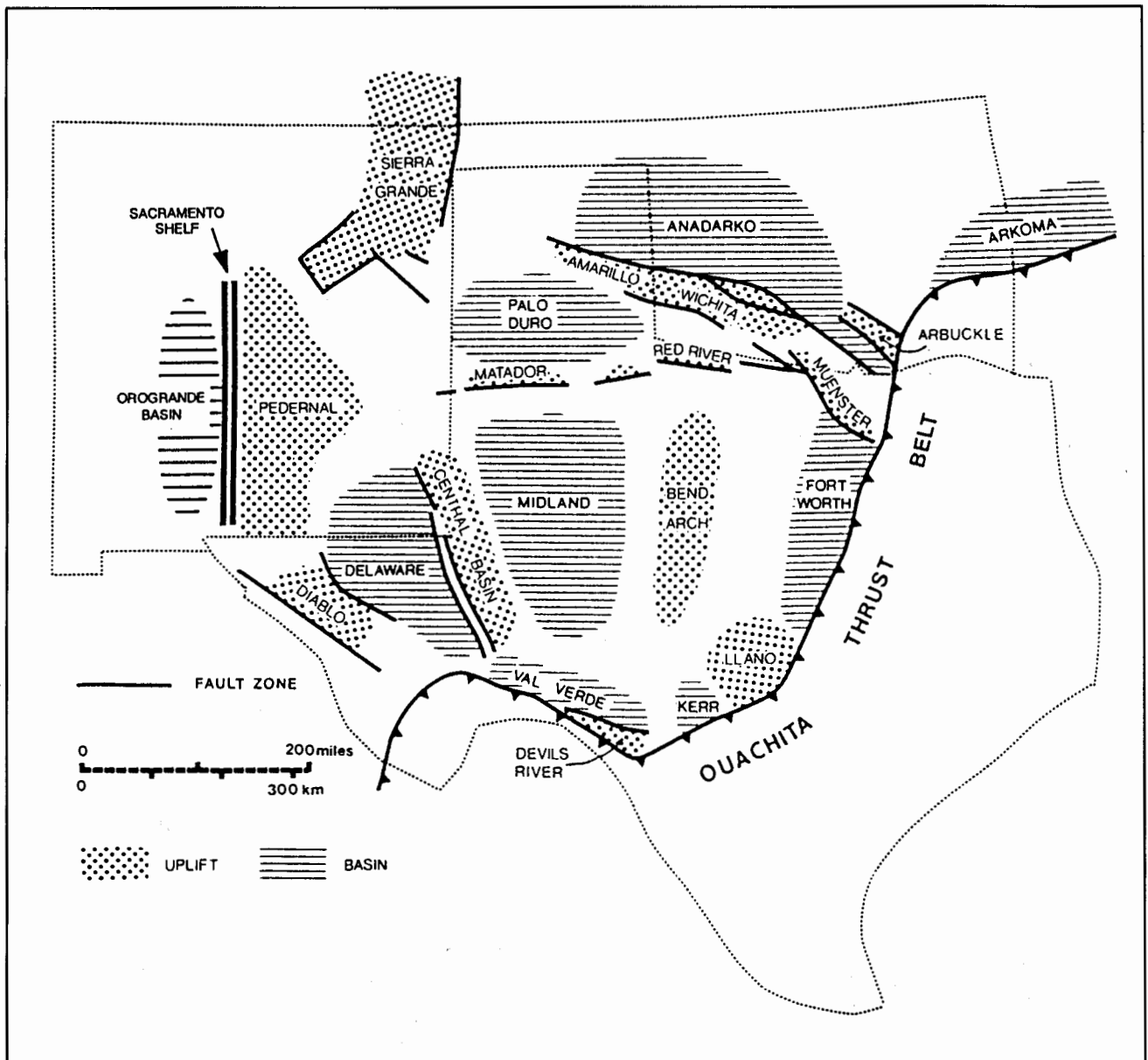
## INTRODUCTION

The importance of wrench faulting within the broadly deformed southwestern margin of Laurussia (the late Paleozoic continent comprising North America and Europe) during the Permo-Carboniferous Ouachita-Marathon Orogeny has gained increasing acceptance, although the details are much in debate. Models have been proposed for continent-scale wrenching that involve either predominantly dextral (e.g., Muehlberger, 1965; Kluth and Coney, 1981; Goetz and Dickerson, 1985; Pindell, 1985; Ross and Ross, 1985; Ross, 1986) or predominantly sinistral shear (e.g., Sales, 1968; Budnick, 1986). Herein, the evidence for these opposing models is reconsidered and an alternative interpretation is offered that allows for Permo-Carboniferous continent-scale wrenching of both right-lateral and left-lateral character.

The key to this new interpretation is the role of the Llano Uplift and adjoining relatively stable areas of central and north Texas (including the Bend Arch, the Eastern Shelf, the midland Basin, and, possibly, the Palo Duro Basin, and herein collectively referred to as the "Llano block"). The Llano block formed a structural promontory on the southwestern margin of the North American craton during the early to middle Paleozoic (Thomas, 1977). This block was bounded by three broad zones of deformation: 1) to the north, the Amarillo-Wichita Uplift in the Texas

Panhandle and southern Oklahoma, 2) to the southwest, the Texas Lineament *sensu lato* in south and west Texas and extending into northern Mexico, and 3) to the west, the western Permian Basin area (including the Central Basin Platform, the Delaware Basin, and the Pedernal Uplift in west Texas and southern New Mexico (Figure 1).

Faulting within these zones of deformation exhibits a combination of dip-slip (mostly high-angle normal and reverse) and strike-slip motion. The sense of strike-slip offset along the Amarillo-Wichita Uplift is predominantly left-lateral (Budnick, 1986; McConnell, 1989; McConnell et al., 1990), while that along the Texas Lineament and along the margins of the major tectonic elements of the western Permian Basin area is predominantly right lateral (Harrington, 1963; Muehlberger, 1965; Hills, 1970, 1984; Goetz and Dickerson, 1985). The conundrum lies in how to interpret regional structural kinematics to account for these contrasting senses of motion and, further, how to reconcile such kinematic interpretations with the fact that the Llano block was a structural promontory during the Paleozoic. The conventional view has held that suturing of Laurussia and Gondwana progressed in a more-or-less linear fashion from the northern Appalachian Mountains in the northeast to the Marathon Mountains in the southwest. According to this view, the parts of the Laurussian conti-



**Figure 1. Late Paleozoic tectonic elements of Texas, Oklahoma, and New Mexico (modified from McConnell 1989). The “Llano block” includes the Llano Uplift, the Bend Arch, the Midland Basin, and, possibly, the Palo Duro Basin.**

mental margin which first came into contact with Gondwana were structural promontories such as the Llano block rather than structural reentrants such as the Mississippi and Marathon embayments (e.g., Thomas, 1977, 1983; Kluth and Coney, 1981; Goetz and Dickerson, 1985; Ross and Ross, 1985; Ross, 1986). However, the structural kinematics implicit in this scenario require northwestward displacement of promontories relative to adjacent embayments, whereas, in fact, the sense of offset on faults bounding the Llano block record displacement in the opposite sense (i.e., to the southeast relative to adjacent areas). To resolve this conundrum, this contribution: 1) reviews evidence of regional wrench faulting and compressive deformation along the margins of the Llano block (focusing to

some extent on the Sacramento Mountains; see also the Day 2 Road Log this volume), 2) examines the timing and sense of fault motion to delineate regional stress fields during the Ouachita-Marathon orogeny, and 3) integrates these data into a new kinematic model for the southwestern margin of Laurussia during Pennsylvanian and early Permian time. The model calls for suturing of the irregularly curvilinear margins of Laurussia and Gondwana in a such a manner that the Llano block was caught in a “tectonic vise” between the North American craton and the Mexican Peninsula, resulting in southeastward “tectonic escape” of the block until further progress was halted by contact with the Gondwanan lithospheric margin.



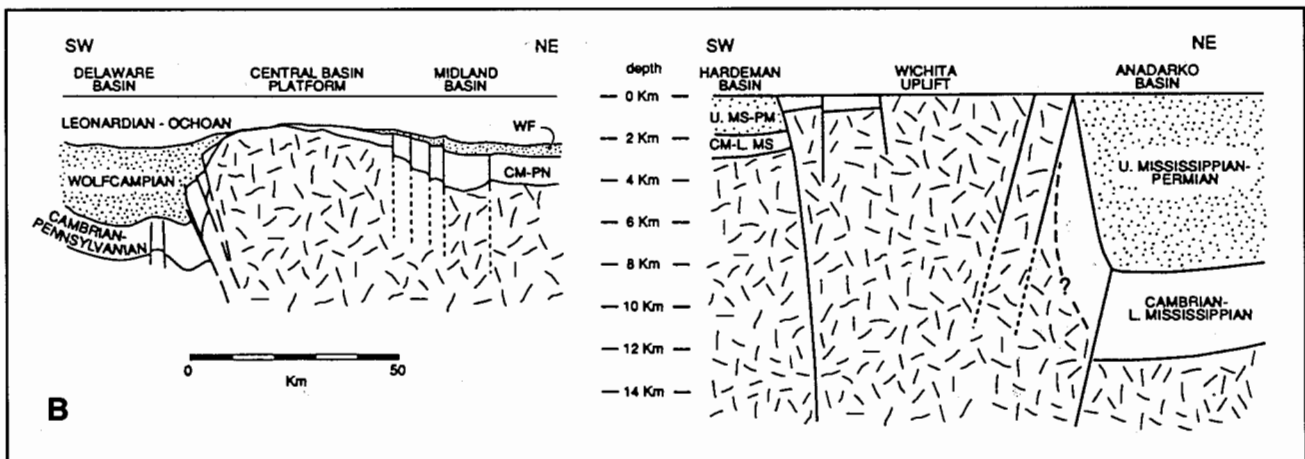
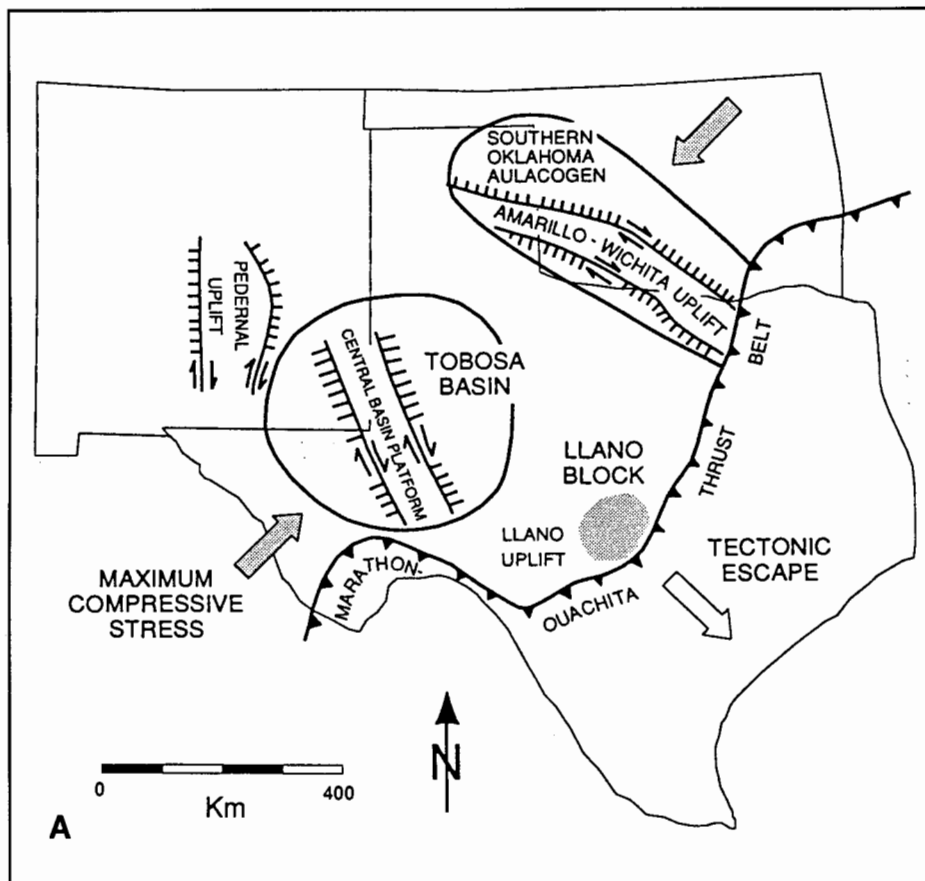


Figure 2. A) Origin of the Amarillo-Wichita Uplift and Central Basin Platform as normally-faulted, late Precambrian-to Cambrian-age grabens of probable aulacogenic origin. These uplifts initially formed the axes of the Early-Middle Paleozoic ancestral Anadarko (Southern Oklahoma Aulacogen) and Tobosa basins, respectively. The Pederal Uplift represents the western margin of deformation of the Permian Basin area. B) Northeast-southwest-directed compression during Pennsylvanian time reactivated these basement discontinuities as transpressional faults, forming flower structures along their margins and producing 8-15 km of structural relief.

## WRENCH FAULTING ALONG THE NORTHERN MARGIN OF THE LLANO BLOCK

To the north, the Llano block was bounded by the Amarillo-Wichita Uplift, extending from the northern Texas Panhandle to south-central Oklahoma and probably in structural continuity with the Arbuckle Mountains in southeastern Oklahoma. Early to late Pennsylvanian displacements along this zone were predominantly reverse left-lateral (Tanner, 1967; Budnik, 1989; McConnell, 1989; McConnell et al., 1990) (Figure 3). The amount of horizontal offset is in dispute, however, with estimates ranging from no more than 12-26 km (McConnell, 1989) to some 120-150 km (Budnik 1986, 1989). The former estimates are based on offset isopachs of the Upper Ordovician-Devonian Hunton Group along the Mountain View fault system, the major boundary fault along the northern margin of the Wichita Uplift, while the latter estimates are based on offset subcrop patterns beneath a regional middle Devonian unconformity surface and represent cumulative displacement across the entire width of the Amarillo-Wichita Uplift.

The timing of displacement within this zone is constrained by the age of the oldest rocks on the uplifted and eroded crest of the Amarillo-Wichita Uplift and by the age of the youngest deformed strata adjacent to the boundary faults (McConnell et al., 1990). Although movement commenced along the entire zone during Morrowan (early Pennsylvanian) time, cessation of slip on different segments of the fault system was diachronous: movement on the Amarillo segment (to the northwest) ceased during the Morrowan or Atokan (Early Pennsylvanian), but movement on segments progressively further to the southeast continued later (until early Permian time in the southeastern Anadarko Basin; McConnell et al., 1990). Peak uplift along the Amarillo Uplift occurred during the Desmoinesian as indicated by the large quantity of arkose shed into small adjoining pull-apart basins such as the Carson and Tascosa Basins (Budnik, 1989).

Enechelon shear folds along the southern margin of the Anadarko Basin (Evans, 1979) and offset of pre-Middle Devonian subcrop patterns along the southern border of the Amarillo Uplift (Potter County Fault; Budnik, 1989) provide further evidence of sinistral strike-slip motion across the full width of the Amarillo-Wichita Uplift (Figure 3). Left-lateral strike-slip motion of Late Pennsylvanian age has been documented in the Arbuckle Mountains (Tanner, 1967). Other subparallel (WNW-ESE to E-W-trending) basement uplifts such as the Oldham-Harmon Trend and the Matador Red River Arch formed during the Desmoinesian and remained active through the late Pennsylvanian or early Permian (Budnik, 1989) (Figure 3).

## WRENCH FAULTING ALONG THE SOUTHWESTERN MARGIN OF THE LLANO BLOCK

To the southwest, the Llano block was bounded by the Texas Lineament *sensu lato*. This zone of deformation was relatively broad, comprising a series of WNW-ESE-trending faults, monoclines, and lineaments in west Texas, southeastern New Mexico, and, probably, northern Mexico (although little is known of Paleozoic movements on features south of the Texas Lineament *sensu stricto* owing to Jurassic wrenching and Cretaceous Laramide thrusting). In west Texas and southeastern New Mexico, these features include the Huapache and Pecos lineaments (also known as Kelley's Shear) (Trollinger, 1968; Kelley, 1971; Goetz, 1985), the Hondo Valley fold belt (Goetz, 1985), the Otero Fault (Goetz, 1985), the Apache Mountain Fault, Victorio and Babb flexures (Trollinger, 1968; Muehlberger, 1980; Goetz, 1985), the Texas Lineament (Muehlberger, 1980; Goetz, 1985), and the Valentine Fault Zone (Goetz, 1985) (Figure 3). These structures are in-line with similarly-oriented features to the northwest (e.g., the Alamo Trough and southern Sacramento Shelf margin; Algeo 1989) and to the southeast (e.g., the Val Verde Lineament, Webster, 1980; and the Devil's River Uplift, Muehlberger, 1980) (Figure 3). Collectively, these features have been interpreted to represent a major dextral crustal wrench zone (Muehlberger, 1965, 1980; Goetz, 1985; Goetz and Dickerson, 1985), an idea supported by close correspondence with deeply-rooted gravity and magnetic anomalies (Keller et al., 1983; Keller and Peebles, 1985; Ewing, 1990). Although some of these faults were reactivated during the Cretaceous in a left-lateral sense (e.g., the Carta Valley fault zone; Webster 1980), Late Paleozoic motion was probably right-lateral transpressional.

Shear folds may be present also along the southern margin of the Delaware Basin, of which the Grisham and Nine-Mile anticlines are probable examples (Trollinger, 1968). Other folds of late Pennsylvanian-early Wolfcampian age have been described from the southern margin of the Diablo Platform (e.g., Pipeline Valley Anticline and Coyote Valley Syncline, Beard, 1985) and may have originated as a consequence of basement wrenching.

## DEFORMATION ALONG THE WESTERN MARGIN OF THE LLANO BLOCK

To the west, the Llano Block was bordered by a broad zone of crustal deformation extending from the Central Basin Platform westward to the Pedernal Uplift (Figure 3). The west side of the Pedernal Uplift, the Sacramento Shelf, is exceptionally well studied owing to the availability of good exposures, and structural features of Permo-Pennsylvanian age are discussed below in detail. Coeval structures



on the east side of the Pedernal Uplift (Northwest Shelf of the Delaware Basin) are comparatively poorly developed, and those from the Central Basin Platform are known only from the subsurface.

### **Sacramento Shelf**

The Pedernal Uplift and the Orogrande Basin adjoining it to the west became distinct tectonic elements during middle Pennsylvanian time (Figure 1). These tectonic elements were separated by a series of north-south-trending faults, of which the main one probably coincided with the Cenozoic-age frontal fault of the modern Sacramento Mountains (Pray, 1961) (Figure 4). Both the Orogrande Basin and Pedernal Uplift were inclined eastward so that substantial relief existed within the narrow, highly-faulted zone between the blocks, a shallow-marine area termed the "Sacramento Shelf."

Most structural features within the Sacramento Mountains developed during the Permo-Carboniferous Marathon Orogeny (Pray, 1977b), and Cenozoic-age faulting is largely confined to the present frontal fault (with an estimated throw of 7000+ (2.2 km) (Pray, 1961) and a series of small subparallel normal faults to the east (Wilson, 1967). Peak deformation of the Sacramento Shelf occurred in late Virgilian and early Wolfcampian time, and, although Permian-age strata were subsequently folded gently, strong faulting and folding are largely confined to pre-Laborcita units outcropping in a 5- to 8-km-wide band along the western margin of the Sacramento Mountains (Pray, 1961). The main structural features of Permo-Pennsylvanian age are: 1) the Alamo Trough, 2) the Fresnal Fault and related faults, 3) the La Luz Anticline, Dry Valley Syncline, and related folds, 4) local erosional domes, and 5) low-angle thrust faults along the frontal escarpment (Figure 4). All township and range locations are given with reference to the geologic maps of the Sacramento Mountains by Pray (1961), his plates 1 and 2).

Alamo Trough. The Sacramento Shelf was bisected by the Alamo Trough (T16S & T17S, R10E), an intrashelf graben probably bounded by high-angle faults with components of both vertical and strike-slip motion (Figure 4) (Algeo, 1989). The graben was asymmetric, exhibiting stronger structural and topographic relief to the south as shown by localized concentrations of coarse clastics and gravity-flow deposits and by rapid facies changes from deep-water sandstones and spiculitic limestones to shelf carbonates along the southern graben margin (Van Wagoner, 1977a, b; Algeo, 1989). Clastics were derived from sources in the Pedernal Uplift to the east and northeast and transported west-northwestward parallel to the graben axis (Pray, 1961; Van Wagoner, 1977a, b). Subsidence of the Alamo Trough occurred intermittently during early-middle Desmoinesian time, but appears to have ceased by the late Desmoinesian when carbonate sedimentation occurred across the entire Sacramento Shelf. Strike-slip movement

along the Alamo Trough boundary faults is suggested by alignment with major WNWSE-trending structural features of the Delaware Basin, (e.g., Huapache Lineament; Kelley, 1971), and by possible offset of the western margin of the Sacramento Shelf.

Fresnal Fault and related faults. The Fresnal Fault (T16S, R10E, Secs. 1, 12) is a major, N-S-trending high-angle normal or reverse fault of Virgilian and early Wolfcampian age (Figure 4). At its intersection with U.S. Highway 82 just west of the Fresnal Canyon tunnel, the fault strikes slightly east of north, dips 70-degrees to the west, and has a throw of ca. 500 m (Delgado and Pray, 1977). The major phase of fault movement was post-Holder (Virgilian) and pre-Abo (early-middle Wolfcampian) (Otte, 1959).

During this episode, several hundred feet of late Pennsylvanian sediments were eroded from the upthrown eastern side of the fault, locally cutting as deeply as the Middle Pennsylvanian Gobbler Formation prior to deposition of the Wolfcampian Abo Formation. On the downthrown western side of the fault, thick sections of the Virgilian Holder and Early-Wolfcampian Laborcita formations were deposited in the Dry Canyon Syncline. In post-Abo time, the fault exhibited mild scissors movement as the eastern block was rotated several hundred feet up to the south (Delgado and Pray, 1977).

Related Late Pennsylvanian-Early Permian faults with probable components of strike-slip motion include: 1) the Alamo Fault, a scissors fault with ca. a few hundred meters of right-lateral offset (T17S, R10E, Secs. 1, 12), and 2) the Bug Scuffle Fault, another scissors fault with, perhaps, as much as 1.5 km of right lateral offset (T19S, R11E, Secs. 22, 27, 34). Several shorter penecontemporaneous faults strike parallel to the Fresnal Fault but exhibit substantially less throw. These features may represent reactivated structural discontinuities of Precambrian age (Pray, 1961).

La Luz Anticline, Dry Valley Syncline and related folds. Beginning in Missourian time and continuing through the early Wolfcampian, broad N-S- to NNW-SSE-trending folds developed within the Sacramento Shelf, controlling sediment thickness and facies patterns (Wilson, 1967; Pray, 1977b). The most prominent folds in the northern Sacramento Mountains are the La Luz Anticline and Dry Canyon Syncline (Figure 4). The former is roughly symmetrical in cross-section, has maximum dips on its limbs of ca. 30 degrees, and plunges at an angle of about 10 degrees to the north. The latter feature is strongly asymmetric (its eastern limb dips as steeply as 70 degrees) and plunges to the north. Other syndepositional folds developed coevally, including the Mule Peak anticline (Wilson, 1967) (Figure 4).

The La Luz Anticline exerted a relatively weak influence on deposition of the Missourian Beeman Formation, resulting in slight thinning of strata across the fold axis and in down dip progradation of dark-colored poorly-sorted oolitic grainstones (D-1 marker bed) both westward and eastward from the fold crest (Wilson, 1967). Anticlinal growth accelerated during deposition of the Virgilian Holder

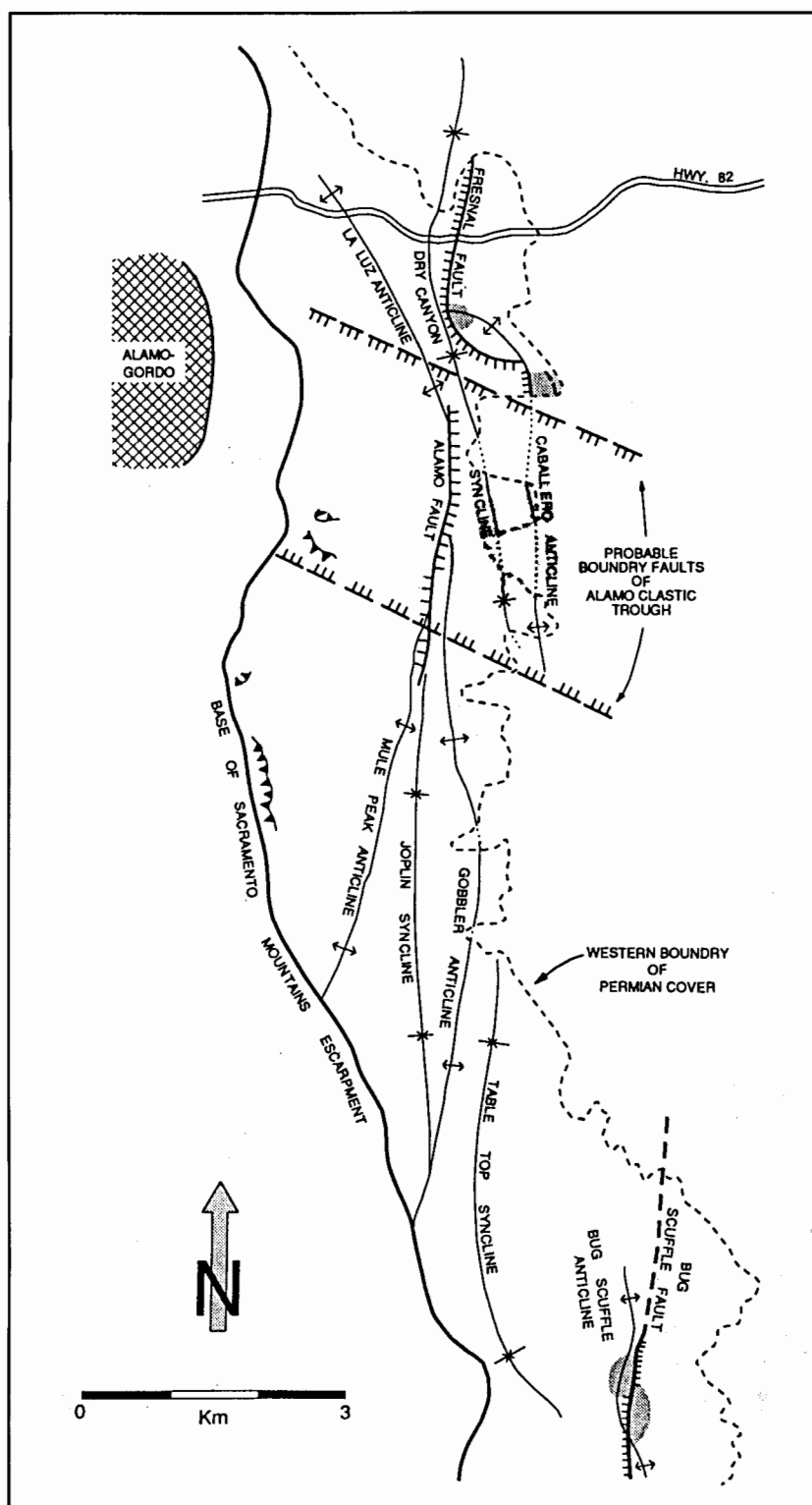


Figure 4. Structure map of the Sacramento Mountains (redrawn with modifications from Pray, 1961). The Alamo Trough is the main intrashelf structural feature of Middle Pennsylvanian age. During the Late Pennsylvanian, numerous faults (e.g., Fresno Fault), folds (e.g., La Luz Anticline), and domical uplifts (e.g., along the Caballero Anticline and Bug Scuffle Fault; shaded) developed along trends subparallel to the Sacramento Mountains escarpment. Low-angle thrust faults along the frontal escarpment are probably early Wolfcampian age.

Formation, resulting in marked crestral thinning and lateral facies control. The basal Holder units comprise a complex of offlapping algal-plate bioherms ("mound layer") about 1 km wide and at least 3 km long that migrated down dip along the fold crest (Wilson, 1967). Syndepositional growth of the anticline resulted in thinning or non-deposition of individual Holder Formation cycles across its crest, the magnitude of which is indicated by cumulative thinning of cycles 4-9 from >70 m on the flank to <30 m on the crest of the structure. Fold growth exerted control on facies and diagenetic patterns, localizing phylloid algal bioherms on the flanks and grainstone shoal units and subaerial exposure surfaces on the crest of the structure.

**Erosional domes.** Local domical uplifts developed intermittently along the upthrown margins of some intrashelf faults, resulting in erosional truncation of strata as deeply as the Ordovician El Paso Formation (Pray, 1961). The most prominent of these are: 1) the dome on the Fresnal Fault in upper Dry Canyon (T16S, R11E, Sec. 7), 2) the dome along a locally-upfaulted portion of the Caballero anticline in upper Arcente Canyon (T16S, R11E, Secs. 17, 20), and 3) the dome on the Bug Scuffle Fault in upper Grapevine Canyon (T19S, R11E, Secs. 22, 27, 34) (Figure 4). The Grapevine Canyon dome appears to have formed prior to the Bug Scuffle Fault, which then truncated it and displaced the western half ca. 1.5 km northward with respect to the eastern half (although pure scissors rotation on the Bug Scuffle Fault might also have produced this outcrop pattern). The location of most erosional domes at sharp bends in major intrashelf faults and folds suggests that they formed through compressional upwarp at the restraining bends of strike-slip faults (e.g., Christie-Blick and Biddle, 1985).

**Frontal escarpment thrust faults.** Compressional deformation of the western margin of the Sacramento Shelf in early Wolfcampian time produced a series of low-angle thrust faults and recumbent folds (incipient thrusts) close to the present Sacramento Mountains frontal escarpment (Pray, 1977a) (Figure 4). Fault-plane dips are generally 20-30 degrees W, and fault offsets are relatively small (<60 m; Pray, 1977a). Although these thrust faults largely die out within relatively incompetent units of the Percha, Caballero, and Lake Valley Formations, they locally penetrate the Pennsylvanian section and are themselves cut by Tertiary block-fault-related dikes, indicating probable formation during the early Wolfcampian culmination of the Marathon Orogeny. The main thrust faults are located in Alamo Canyon (T16S, R10E, Sec. 34, and T17S, R10E, Secs. 3 and 4), Arrow Canyon (T17S, R10E, Secs. 17 and 20), and San Andres Canyon (T17S, R10E, Secs. 28 and 33).

**Summary of Sacramento Shelf Structures.** The faults and folds discussed above are indicative of at least two episodes of deformation of the Sacramento Shelf. Middle Pennsylvanian tectonism was limited to high-angle block faulting along the western shelf margin and the Alamo Trough. During late Pennsylvanian-early Wolfcampian time, dextral transpressional shear produced first the La

Luz Anticline and related folds, then the Fresnal Fault and related faults, and finally the thrusts along the frontal escarpment, reflecting a progressive increase in the intensity of intrashelf deformation. Although the orientation of principle stress axes during the middle Pennsylvanian is unclear, the N-S and NNW-SSE trend of late Pennsylvanian shear folds indicates a principle stress axis oriented approximately northeast-southwest during the late Pennsylvanian. Early Wolfcampian thrusting might have occurred under generally east-west compression.

### **Northwestern Shelf of the Delaware Basin**

The eastern margin of the Pedernal Uplift (Northwest Shelf of the Delaware Basin) is characterized mainly by a series of NE-SW-trending faults and lineaments of which the most prominent features are the White Tail-Serrano Buckle, and the Border, 6-Mile, and Y-0 faults (Kelley, 1971; Goetz, 1985) (Figure 4). The lateral component of offset on these faults is thought to have been dextral, although the magnitude and timing of offset are undetermined.

### **Central Basin Platform**

Subsurface work has shown that boundary faults on most of the major tectonic blocks in the Central Basin Platform area exhibit strike-slip motion, and that, where basement faults do not penetrate the Paleozoic sediment blanket, shear folds record the sense of lateral offset. Two main sets of faults are present in the Central Basin Platform area. The platform is bounded by N-S or NNW-SSE-trending faults along its eastern and western margins (Harrington, 1963; Hills, 1970, 1984) and is transected by a series of E-W or WNW-ESE-trending faults that delineate tectonic blocks within the platform (Ewing, 1991) (Figure 4). The boundary faults (West and East Platform faults; Harrington, 1963) exhibit right lateral strike-slip offset (Hills, 1970, 1984; Walper, 1977). The West Platform Fault also exhibits high-angle thrusting and development of positive "flower structures" (Figure 2B), which are characteristic of transpressional fault zones (e.g., Harding 1985). Right-lateral strike-slip movement may have occurred also along the Roosevelt positive, to the north of the Central Basin Platform, where 25-km dextral offset was recognized on the Roosevelt County Fault (Flawn, 1956); (Figure 4). In contrast, faults transecting the Central Basin Platform (e.g., Pecos Valley Fault, Hills, 1970; Big Lake and Todd Elkhorn faults; Ewing, 1991) have a more easterly orientation (ca. N60W-S60E to E-W) than the main boundary faults and differ in exhibiting predominantly left-lateral offset (Figure 4).

Paleozoic strata of the Central Basin Platform are widely deformed by shear folds, which are generally asymmetric in crosssection and internally fault-dissected, range in structural height up to 600 m or more, and form petroleum traps (Frenzel et al., 1988) (Figure 4). These anti-



Chesterian (late Mississippian) and accelerated during the Morrowan-early Atokan Wichita Orogeny (Frenzel et al., 1988) (Figure 6). The main phase of tectonism in this area was the late Atokan-Desmoinesian Ouachita orogeny, which resulted in intense folding and faulting along the frontal belt and deposition of coarse conglomeratic molasse in the adjacent Anadarko Basin. The last phase of tectonism was the Virgilian-early Wolfcampian Arbuckle Orogeny, which was characterized by reactivation of older thrust faults. Cumulative foreshortening across the Ouachita Orogen was at least 80 km (Ham and Wilson, 1967).

Deformation in the Permian Basin area commenced in the Late Mississippian, coeval with the Wichita Orogeny, resulting in the formation of broad folds on the Central Basin Platform over which Mississippian to Precambrian strata were locally stripped away by early Pennsylvanian time (Hills, 1970). In West Texas and southeastern New Mexico, subsidence of the Midland and Delaware basins accelerated during Atokan-Desmoinesian time, roughly coincident with the peak of the Wichita Orogeny and the initial phases of the Marathon Orogeny (Figure 6). Peak subsidence in the Permian Basin area occurred during Virgilian-early Wolfcampian time, coincident with the Arbuckle Orogeny and the main phase of the Marathon Orogeny (Ham and Wilson, 1967; King, 1980; Ross and Ross, 1985; Frenzel et al., 1988) (Figure 6). Strong reverse and thrust faulting, in combination with regional uplift, occurred along the margins of tectonic blocks of the Permian Basin area at this time (Wilson and Jordan, 1988) (Figure 2B).

The eastern and central parts of the Llano block were most affected by the middle Pennsylvanian Ouachita Orogeny. Uplift of the Llano block during the Atokan-Desmoinesian is indicated by deposition of clastic alluvial and deltaic sediments in the Kerr Basin to the south (Frenzel et al., 1988). During this time, the Llano Uplift and adjoining Fort Worth Basin developed an en echelon series of N-S to NE-SW-oriented normally-faulted horsts and grabens that exhibited a component of right-lateral strike-slip motion (Johnson and Becker, 1986; Johnson et al., 1988; Amsbury and Haenggi, 1991). Coeval deformation within the Llano block occurred along the N-S-oriented Fort Chadbourne fault system, on which movement peaked during the Atokan and early Desmoinesian and waned during the remainder of Pennsylvanian time (Rall and Rall, 1958).

This brief synopsis highlights several important points relative to the timing of late Paleozoic tectonic events on the southwestern margin of Laurussia: 1) the general simultaneity of events on the various margins of and within the Llano block, 2) differences in the timing of peak tectonism from early-middle Desmoinesian in southern Oklahoma to middle Virgilian-early Wolfcampian in west Texas-New Mexico (Ham and Wilson, 1967), and 3) middle Pennsylvanian deformation of transtensional (rather

than transpressional) character along the Ouachita-Marathon Front southeast of the Llano block.

## STRUCTURAL KINEMATICS

Early to middle Pennsylvanian intracrustal stresses originated mainly along the Appalachian-Mauritanide Front in eastern North America (Budnick, 1986) and were oriented approximately east-west (Hills, 1970; Font, 1985).

This set up a left-lateral transpressional wrench system along the ca. N70W-S70E-oriented Amarillo-Wichita Uplift, which can be resolved into strike-parallel (ca. N70W-S70E) and strike-normal (ca. N20E-S20W) components (Figure 7). During the late Pennsylvanian and Wolfcampian, the locus of tectonic activity shifted southwestward to the Marathon region. Right-lateral transpression occurred along faults oriented between N50W-S50W and N60W-S60E within a broad wrench zone extending from the Texas Lineament *sensu lato* southward for an unknown distance. Motion within this wrench zone can also be resolved into strikeparallel (ca. N55W-S55E) and strike-normal (ca. N35E-S35W) components (Figure 7).

These shear couples resulted in southeastward displacement of the intervening Llano block relative to the North American craton and the ancestral Mexican Peninsula (Figures 2A, 7). Further, the strong transpressional character of shearing set up an approximately NNE-SSW-oriented maximum principle stress axis within the Llano block. Owing to the difference in orientation between the Amarillo-Wichita Uplift (ca. N70W-S70E) and the Texas Lineament *sensu lato* (ca. N55W-S55E), this maximum principle stress axis produced a "tectonic vise," reinforcing the relative southeastward displacement of the Llano block, which was but weakly opposed by the flysch-filled Ouachita foredeep basin.

Deformation of the broad western margin of the Llano block reflects this NNE-SSW-oriented maximum principle stress axis. Although the overall pattern is rather complex (e.g., Hills, 1970; Ewing, 1991) several distinct trends are apparent. Faults striking to the north of the trend of the Texas Lineament *sensu lato* (mostly N30W-S30E to N-S), such as the Sacramento Mountains frontal fault, the Roosevelt County Fault, the West and East Platform faults, and the Puckett Fault, tend to exhibit right-lateral offset (Figure 3). In contrast, faults striking to the west of that trend (mostly N60W-S60E to E-W), such as the Grisham, Pecos Valley, Big Lake, and Todd Elkhorn faults, tend to exhibit left-lateral offset (Figure 3).

The overall pattern of deformation suggests lateral displacement and, possibly, rotation of small tectonic blocks caught between the convergent wrench systems to the north and south of the western Permian Basin area. This "tectonic jostling" appears to have caused: 1) right-lateral wrenching along the eastern and western margins of both

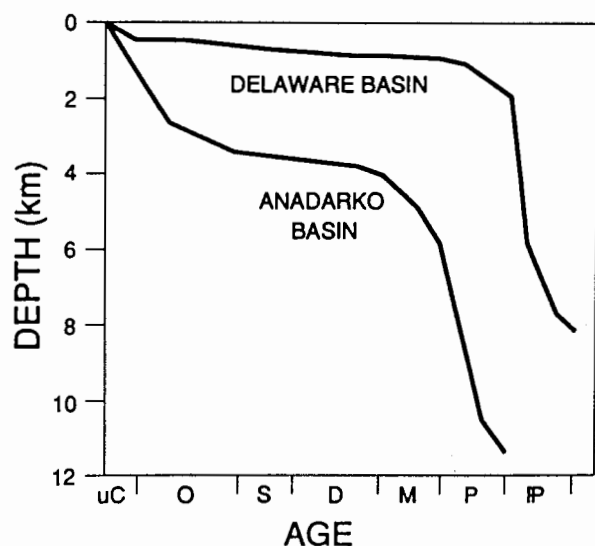


Figure 6. Subsidence histories of the Delaware and Anadarko basins. Tectonic subsidence of the Anadarko Basin commenced in the Early Mississippian and accelerated in the Early Pennsylvanian, whereas that of the Delaware Basin commenced in the Early Pennsylvanian and accelerated in the Late Pennsylvanian-Early Permian. Maximum subsidence of the Anadarko Basin (ca. 12 km) exceeds that of the Delaware Basin (ca. 8 km).

the Central Basin Platform and the Pedernal Uplift, 2) formation of shear folds, especially along the more strongly deformed western margins of these uplifts, and 3) dissection of the Central Basin Platform along E-W and WNW-ESE-trending transverse faults, with eastward displacement of blocks at the southern end of the platform in relation to those at the northern end.

Whereas the northern, western, and southwestern margins of the Llano block were characterized by transpressional deformation, its eastern margin exhibited a tensional component to faulting during the middle Pennsylvanian. This is consistent with a NNE-SSW oriented maximum principle stress axis (but not with northwest directed Ouachita Front thrusting), although normal faulting may have been caused in part by crustal flexure associated with foredeep loading (Johnson and Becker, 1986). Right-lateral offset along the Llano fault zone (Amsbury and Haenggi, 1991), in combination with left-lateral offset along the Fort Chadbourne fault zone (Rall and Rall, 1958; Ewing, 1991), suggests that the Llano Uplift-Bend Arch region moved northward relative to adjacent areas during the early to middle Pennsylvanian.

The maximum principle stress axis within the Llano block and surrounding areas may have been reoriented to a roughly WNW-ESE direction by early Wolfcampian time. This is suggested by strong compressional deformation in this sense associated with the terminal phase of the Marathon Orogeny. Such deformation includes low-angle thrusting along the Sacramento Mountains frontal escarpment, the frontal Marathon thrust (Dugout Creek Fault), and

along the Ouachita-Marathon Thrust Front in the subsurface east of the Llano Uplift, which resulted in widespread truncation of existing Pennsylvanian folds and faults (Nicholas and Waddell, 1989). In addition, this event may have reactivated in a reversed sense existing secondary faults within Central Basin Platform shear folds (e.g., Halley Field anticlines, this paper). This final thrust episode may mark impingement of the Llano block against the Gondwanan lithospheric margin, resulting in cessation of its southeastward "tectonic escape" and subsequent transmission of compressional stresses across its southeastern margin.

This model is broadly consistent with previous kinematic interpretations, although some differences exist with respect to the orientation of principle stress axes. A generally NE-SW oriented principal stress axis has been proposed for both the Wichita Uplift area (Brewer et al., 1983) and the Central Basin Platform area (Harrington, 1963) during the Pennsylvanian. (Hills, 1970; and Font, 1985) postulated two stress regimes to account for fault patterns in the Permian Basin area: 1) a relatively weak ENE-WSW-directed, during late Mississippian and early Pennsylvanian time, and 2) a much stronger N-S-directed axis during late Pennsylvanian and early Permian time. Data discussed herein favor a NNE-SSW-oriented axis, during the Middle to Late Pennsylvanian with a brief(?) reorientation in the Wolfcampian to a strongly WNW-ESE-oriented.

## PLATE TECTONIC MODEL

The Late Paleozoic collision of Laurussia with Gondwana set up broad intracrustal stresses that resulted in tectonism at least as distant as the ancestral Rocky Mountains (>1000 km; e.g., Kluth and Coney, 1981; Budnik, 1986). Models proposed to account for cratonward transfer of stresses generated at the continental margin have invoked both predominantly dextral (e.g., Muehlberger, 1965; Kluth and Coney, 1981; Goetz and Dickerson, 1985; Pindell, 1985; Ross and Ross, 1985) and predominantly sinistral (e.g., Sales, 1968; Budnik, 1986) continent-scale wrenching. Although these models appear to be fundamentally at odds, they are based largely on consideration of different tectonic zones and, thus, are potentially reconcilable. Herein, a model is proposed calling for sinistral displacement along the northern margin of the Llano block (Amarillo-Wichita Uplift), dextral displacement along its southwestern margin (Texas Lineament *sensu lato*), and complex deformation of its western margin (western Permian Basin area). This model thus envisions southeastward "tectonic escape" of the Llano block during the middle and late Pennsylvanian until it came firmly in contact with the Gondwanan lithospheric margin.

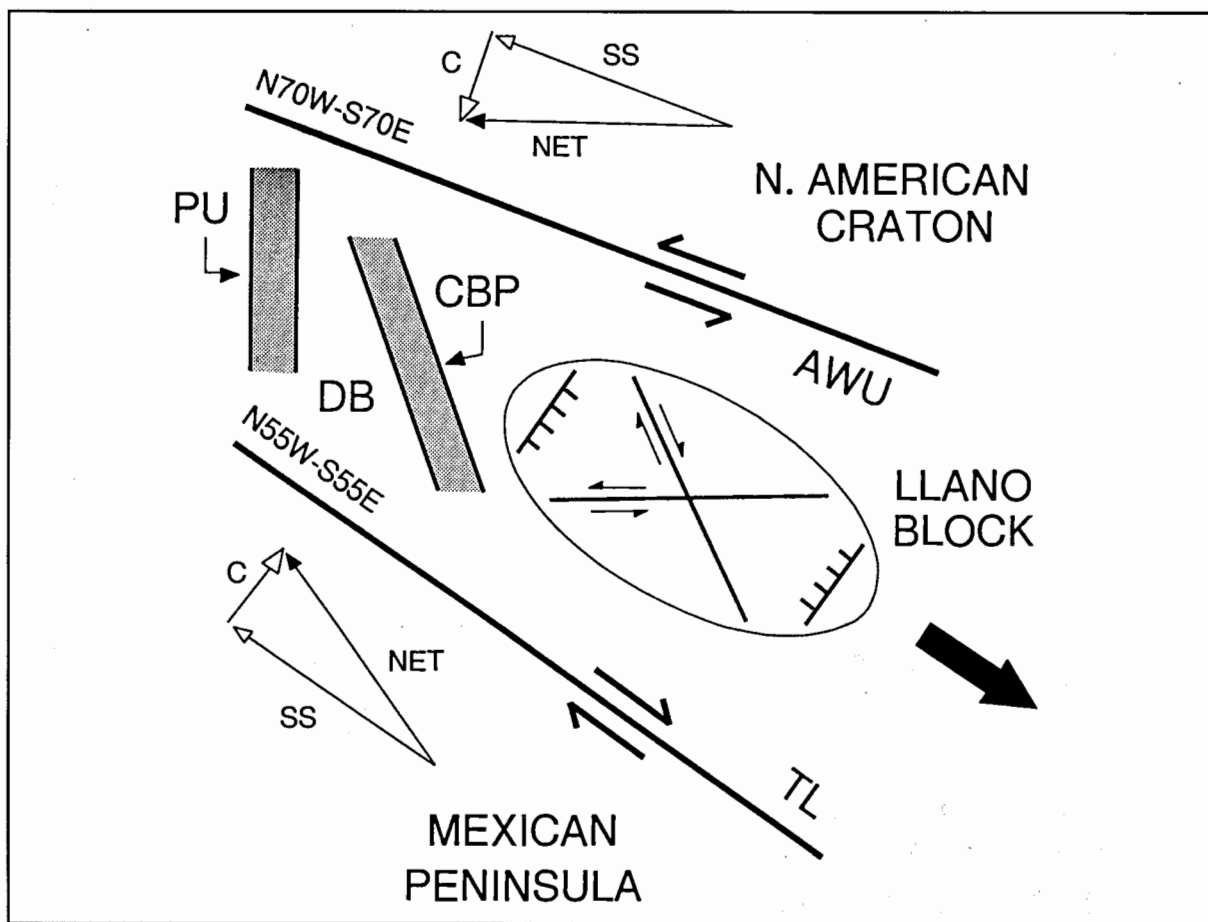
The key to understanding the Late Paleozoic tectonic history of southwestern Laurussia is the recognition that suturing of Laurussia and Gondwana proceeded along irregular continental margins, and that early impingement of structural promontories set up broad intracrustal stresses that were accommodated along continent-scale wrench zones.

Gondwana had been undergoing clockwise rotation since the Ordovician (Scotese and McKerrow, 1990), this rotation apparently continued during continental suturing, resulting in diachronous closure of the Iapetus and Theic oceans (Pique, 1992) (Figure 8). Thus, orogenic activity in the northern Appalachians commenced during the Late Devonian (Acadian Orogeny), in the central and southern Appalachians during the Chesterian (Late Mississippian), and in the Marathon Mountains during the Middle to Late Pennsylvanian (Ham and Wilson, 1967; Graham et al., 1975; Kluth and Coney, 1981; Hatcher, 1989; Pique, 1992).

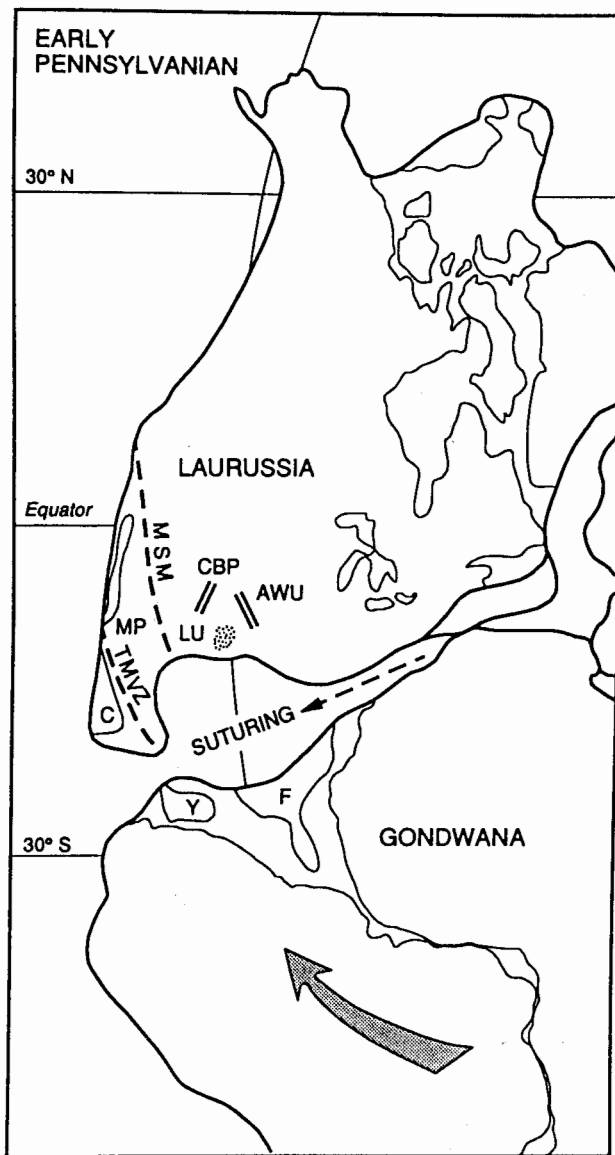
Initiation of left-lateral wrenching along the Amarillo Wichita Uplift (Budnick, 1986) was probably coincident

with orogenic activity in the southern Appalachians, which peaked during the Middle Pennsylvanian and resulted in cumulative crustal shortening of at least 300 km (Cook et al., 1979). At this time, the Appalachian-Mauritanide front (eastern North America-northwest Africa; Pindell, 1985) represented the main collision zone between Laurussia and Gondwana, and the latter continent may not have been in contact with the ancestral Mexican Peninsula (Figure 8).

Continued clockwise rotation of Gondwana eventually brought its northwestern (South American) margin into contact with the southwestern margin of Laurussia (Scotese and Denham, 1987; Scotese and McKerrow, 1990), resulting in formation of the Ouachita-Marathon Orogen



**Figure 7.** Structural kinematics of the margins of the Llano block. Major transpressional faulting occurred along the northern (Amarillo-Wichita Uplift) and southern (Texas Lineament *sensu lato*) margins of the Llano block. Compressional stresses (C) were transmitted in part to the interior of the block, producing a NNE-SSW-oriented maximum principle stress axis during the Middle and Late Pennsylvanian. Under this stress regime, deformation of the Llano block resulted in E-W-oriented left-lateral and NNW-SSE-oriented right-lateral faulting (mainly in the western Permian Basin area) and NNE-SSW-oriented extensional faulting (mainly in the Llano Uplift Bend Arch area; shaded strain ellipse). Differences in the orientation of the Amarillo-Wichita Uplift (N70W-S70E) and the Texas Lineament *sensu lato* (N55W-S55E) and absence of a rigid tectonic barrier to the southeast (prior to complete suturing with Gondwana) permitted southeastward "tectonic escape" of the Llano block. Abbreviations: C = compressional component of net motion, SS = strike-slip component of net motion; AWU = Amarillo-Wichita Uplift, CBP = Central Basin Platform, DB = Delaware Basin, PU = Pedernal Uplift, and TL = Texas Lineament *sensu lato*. The figure is highly generalized and not to scale; relative vector magnitudes are only approximate.



**Figure 8. Reconstruction of western-hemisphere plate positions in the Early Pennsylvanian.** Owing to clockwise rotation of Gondwana (arrow), continental suturing proceeded from north to south during the Late Devonian to Early Permian. Abbreviations: AWU = Amarillo-Wichita Uplift, C = Chortis (modern Nicaragua), CBP = Central Basin Platform, F = Florida, LU = Llano Uplift, MP = ancestral Mexican Peninsula, MSM = Mojave-Sonora Megashear, TMVZ = Trans-Mexican Volcanic Zone, and Y = Yucatan. Projection modified from Scotese and Denham (1987).

and the Huastecan Structural Belt (eastern Mexico; Pindell and Dewey, 1982). It seems likely that Gondwana impinged first on the Mexican Peninsula, and that this structural promontory (and not the Llano block) absorbed the initial impact (Figure 8). Kinematically, this had the effect of pushing the ancestral Mexican Peninsula

northwestward, probably through distributed shear along a series of dextral transpressional wrench faults such as the Texas Lineament *sensu lato* (including the Pedregosa Trough and Devil's River Uplift fault zones; Pindell, 1985) and the proto-Mojave-Sonora Megashear (Anderson and Schmidt, 1983; Pindell, 1985). High-grade metamorphism and thrusting of the Acatlan Complex in southern Mexico (Oaxaca) may evidence (coeval?) deformation to the south (Yafiez et al., 1991). Although the timing of initial contact is not known with any assurance, major wrenching within the ancestral Mexican Peninsula probably accompanied the Virgilian-early Wolfcampian peak of the Marathon Orogeny, which had no counterpart of comparable magnitude to the east.

Once Gondwana had impinged on both the southeastern (Appalachian) and southwestern (Mexican) margins of Laurussia, these two transpressional shear couples created a "tectonic vise" which forced the intervening wedge-shaped Llano block relatively southeastward (Figures 2A, 7). Extrusion continued until the Llano block came firmly into contact with the Gondwanan lithospheric margin, an event marked by strong regional uplift and compressional deformation of all margins of the Llano block during the culmination of the Ouachita-Marathon Orogeny in the early Wolfcampian. The amount of inferred crustal shortening along the Ouachita-Marathon Thrust Front is less adjacent to the Llano promontory (ca. 50 km; Rosendal and Erskine, 1971) than in the neighboring Mississippi (ca. 100 km; Lillie et al., 1983; Lillie, 1985), or Rio Grande embayments (200 km+; Muehlberger and Tauvers, 1989), which is consistent with more intense deformation of the continental margin opposite embayments.

The significance of the "tectonic escape" of the Llano block is that this translation resulted in filling of a "hole" within the collision zone. This highlights an important aspect of the final suturing of Laurussia and Gondwana: the translation and rotation of small tectonic blocks within the collision zone. This process is quite common, e.g., recent models for the suturing of the Alleghenian Orogeny call for lateral migration of small blocks within the collision zone as a result of impingement of Gondwanan structural promontories against the Laurussian continental margin (e.g., Hatcher, 1989). Such "tectonic jostling" may have occurred also along the southwestern margin of Laurussia, where several small exotic terrains were lodged within the reentrants bordering the Llano promontory. These include the Sabine and Monroe uplifts within the Mississippi Embayment, and the Coahuila Platform within the Rio Grande Embayment, all of which are probably remnants of a continent-margin arc system (Pindell and Dewey 1982; Pindell, 1985). Although lateral translation during suturing cannot be demonstrated for most of these blocks, which are either deeply buried (e.g., the Sabine and Monroe Uplifts) or have subsequently migrated to new locations during Jurassic-Cretaceous rifting and opening of the Gulf of Mexico (e.g., the Yucatan, Florida, and

Coahuila platforms), Early Mesozoic pre-rift paleogeographic restorations suggest that they rather neatly filled holes within the collision zone (Pindell and Dewey, 1982; Pindell, 1985), a circumstance requiring either serendipity or a fair amount of "tectonic jostling." At present, only the Llano block provides evidence for such translation (albeit of small magnitude) within the collision zone.

## CONCLUSIONS

- 1) The Llano block, including the Llano Uplift, Bend Arch, Eastern Shelf, Midland Basin, and, possibly, the Palo Duro Basin, represented a stable, internally little-deformed block during the late Paleozoic Ouachita-Marathon Orogeny.
- 2) The Llano block was bounded by broad zones of deformation to the north (the Amarillo-Wichita Uplift), to the west (the western Permian Basin area, extending from the Central Basin Platform to the Pedernal Uplift), and to the southwest (the Texas Lineament *sensu lato*).
- 3) Wrenching along the Amarillo-Wichita Uplift was predominantly left-lateral and peaked during the Late Atokan-Desmoinesian Ouachita Orogeny.
- 4) Wrenching along the southwestern margin of the Permian Basin (the Texas Lineament *sensu lato*) was predominantly rightlateral and peaked during the Virgilian-early Wolfcampian Marathon Orogeny.

- 5) Distributive shear characterized the western Permian Basin area, with right-lateral strike-slip occurring along faults oriented N-S to N30W-S30E (mostly along the margins of major tectonic elements such as the Central Basin Platform and Pedernal Uplift) and left-lateral strike-slip occurring along faults oriented N60W-S60E to E-W (mostly transecting the Central Basin Platform).
- 6) The interior of the Llano block was weakly deformed as the eastern half (Llano Uplift-Bend Arch) was squeezed northward relative to the western half along the Llano Uplift and Fort Chadbourne fault zones.
- 7) The overall pattern of deformation suggests that the maximum principle stress axis was oriented roughly NNE-SSW during the middle and late Pennsylvanian, possibly shifting toward a WNW-ESE orientation as the Llano block came into firm contact with the Gondwanan lithospheric margin during the Early Permian.
- 8) The ambient stress regime and sense of offset along the Amarillo-Wichita Uplift and Texas Lineament *sensu lato* are consistent with southeastward displacement ("tectonic escape") of the Llano block relative to the North American craton and the ancestral Mexican Peninsula during the Ouachita-Marathon Orogeny.

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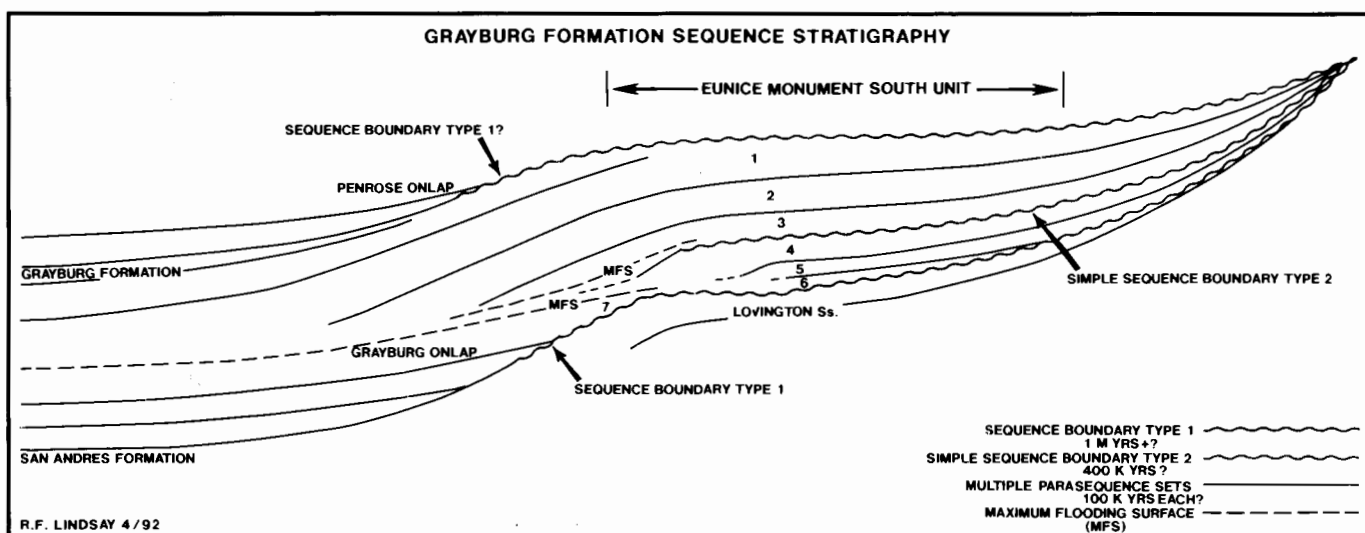
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# SEQUENCE STRATIGRAPHY APPLIED TO PERMIAN BASIN RESERVOIRS: Outcrop Analogs in the Caballo and Sacramento Mountains of New Mexico

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Robert F. Lindsay and Christy L. Reed

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